

Can We Date Starbursts?

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Abstract. Age dating starbursts is an exercise with many caveats. We attempt to summarise a discussion session that was lead along a rather optimistic guideline: the aim was to highlight that current age estimates, despite undeniable uncertainties, do provide constraints on the physics of starbursts. In many cases, better starburst theories will be needed before the improvement of empirical timelines becomes crucial.

1 Introduction

Many questions can be asked about our ability to trace the history of star formation (SF) in starbursts. The phrasing chosen by the Organizing Committee of this workshop was “Can we date starbursts?”. This formulation calls for one of only two answers : *yes*, or *no*.. When hearing the question, one automatically recalls ones most recent conversation about the complexity of starburst galaxies or about uncertainties in stellar population synthesis models. Is there any chance for a positive answer ? In preparing guidelines for the discussion, we took the optimistic approach of attempting to defend a *yes*. Of course the final answer ended up not being as clear-cut, but some negative intuitions were countered.

Clearly, our degree of satisfaction with starburst age or duration measurements depends on the intended application. The initial question really holds two: how accurately and reliably can we date starbursts ? and is that sufficient to make astrophysics progress ?

Starburst galaxies are composite objects. The SF may occur both in a diffuse mode and in clusters [23]. The global duration of active episodes can approach 10^9 yrs, while individual starburst clusters are often thought to form instantaneously ($< 10^6$ yrs). To avoid confusion in the meaning of the word “starburst”, the following pages deal successively with (i) individual young starburst clusters, (ii) individual intermediate age “post-starburst” clusters that trace starburst activity of the recent past, and (iii) starburst galaxies as a whole. More extensive reviews and references regarding the age dating of stellar populations can be found in [19], [12], [14] and in this volume.

2 Individual young clusters

This section focuses on starburst clusters with ages below 10^7 yrs, as observed in large numbers in the main body of starburst galaxies ([7], [29], [1]) or in tidal tails of interacting objects ([29], [8]).

The conditions for cluster age determination are most favourable when the spectroscopic study of individual stars is possible. Until now such studies have been limited to the local neighbourhood of the Milky Way, where many young OB associations exist but massive compact young clusters (as seen in starburst galaxies) are rare/non-existent; 30 Doradus in the LMC and NGC 3603 in the Milky Way are the most relevant accessible targets. Nevertheless, the nearby objects highlight some of the difficulties:

- Samples of cluster stars with spectroscopically confirmed positions in the Hertzsprung-Russell (HR) diagram are small and strongly affected by stochastic fluctuations or spatial variation in the extinction; they are potentially contaminated by field stars.
- Massive star main sequence lifetimes vary between authors by up to $\sim 25\%$.
- Rotation is poorly understood, but rotational velocities above 100 km/s are the rule in early type stars. Meynet (in [12]) shows that the main sequence lifetime of a massive star may be extended by 20–25% in case of rotation.
- The proportion of double stars and the effect of binarity on evolution are unknown. Binaries are usually neglected in predictions of frequently used properties such as the number fractions of various types of Wolf-Rayet stars.

In more distant starburst clusters, one integrates the cluster light. The photospheric and wind features in the UV spectrum are considered the most sensitive age indicators and in principle give instantaneous burst ages to within a few Myr [20]. The study of line equivalent widths allows similar formal age accuracies if the light of the whole H II region surrounding the cluster can be summed, the fraction of escaping Lyman continuum photons considered negligible and the continuum contamination by background stars subtracted. The above-mentioned problems associated with rotation, binarity and stellar tracks remain. Charlot (in [19]) for instance points out a delay of about 0.1 dex (25%) between the appearance of the first red star contributions in two sets of commonly used evolutionary tracks. The risk of stochastic fluctuations between the properties of clusters with identical ages also persists because of fluctuations in the small numbers of very luminous stars. Monte Carlo simulations [4] indicate that these fluctuations contribute less than ~ 1 Myr additional uncertainty to the age estimate as long as clusters more massive than $10^4 M_{\odot}$ are considered.

How the described sources of uncertainties add up or compensate each other is not known. Today, if telescope time is not a limiting factor, a detailed multi-wavelength study of a young cluster can be thought to provide an age estimate to better than $\sim 50\%$. Opinions in the workshop audience varied from 30% (which I would support at least in favourable cases), to a provocative 0.3 dex (which are probably realistic at extreme metallicities or in environments of particularly complex structure).

Can astrophysical questions be addressed with a 50% accuracy in young starburst cluster ages? Problems of physical interest include SF processes themselves (delay between an external trigger and the onset of SF, formation timescale for massive clusters, propagation of SF within a galaxy) and their effects on the en-

vironment (survival times of molecular clouds around starburst clusters, bubble expansion timescales).

Many examples illustrate that spectrophotometric ages, despite the uncertainties, provide interesting constraints. Age spreads of several Myr have been found in OB associations ([30], [2], [26]), showing that a unique number does not suffice to describe their age. WC/WN star number ratios indicate that spreads of a few Myr may also be relevant to clusters in starburst environments [27]. Rather complex age structures are seen in NGC 3606 and 30 Dor. In both cases the massive stars of the youngest, 2-3 Myr old component, are concentrated in the central few parsecs and surrounded with significantly older components ([10], [28]). This situation remains to be convincingly explained by cluster formation models (what are the relative roles of a progressive onset of SF [26], mass segregation [24], [13], propagation, merging?). Oey & Massey [25] studied the LH 47/48 and the surrounding superbubble in the LMC, and found a significant disagreement between the stellar ages and the bubble properties predicted from a simple dynamical model, calling for more detailed modelling of the reactions of the ISM. Uncertainties in the identification of external triggers and in *their* onset time dominate in many studies of the initiation of SF in young clusters. Clearly, spectrophotometric dating has been successful in providing other fields of starburst cluster research with new problems.

3 Individual post-starburst clusters

Star clusters with ages between 10^7 and 10^9 yrs are useful to relate current SF activity to potential starbursts of the recent past. They are often found together with the young clusters discussed previously. As they do not ionize their surroundings and have already faded at optical wavelengths, they have not yet been searched for and studied as systematically as their younger counterparts.

Post-starburst clusters are dominated by B then A type stars in the optical/near-UV, by red supergiants (RSG) and then giants of the upper asymptotic giant branch (TP-AGB) in the near-IR. The effects of mixing processes, due e.g. to rotation, appear essential to explain the location of B stars in the HR diagram [21]; Figueras & Blasi [6] use simulations of the Strömgren photometry of stellar populations with reasonable rotation velocity distribution to conclude that photometric ages are affected at the 30-50% level. More consistent approaches combining the effects of rotation on internal structure and on observable properties have not yet been systematically applied to age studies. Supergiant counts should be used with caution at non-solar metallicities (Z) as the Z -dependence of the blue/red number ratio is not predicted correctly by models [18]. It seems that at $Z_{M31} \simeq Z_{\odot}$ the RSGs have later spectral types but are only produced for $m < 15 M_{\odot}$ (age ~ 12 Myr) as opposed to $m < 25 - 30 M_{\odot}$ (age ~ 7 Myr) at $Z_{NGC6822} \simeq Z_{\odot}/3$ [22]. Modelling the thermal pulses and the Mira-type pulsation along the TP-AGB, in addition to the early AGB, is essential when studying stars in $10^8 - 10^9$ yr old clusters. Number counts that separate C-rich stars from

O-rich stars of various subtypes then are potential age-indicators (Lançon & Mouhcine, this volume, and references therein).

For unresolved solar metallicity clusters younger than ~ 50 Myr, well-isolated from the host galaxy background, the UV features give ages to within $\sim 20\%$ [3]. Effects of metallicity are uncertain, but empirical calibrations are being attempted (Tremonti, this workshop). The absorption line spectrum (H α and metals) *together* with the energy distribution in the Balmer region gives ages to within $\pm 30\%$ ([7], [11]). Reddening-independent colour-indices in [29] are efficient and could be generalised to include near-IR fluxes. Gilbert (this workshop) showed that, at a given metallicity, near-IR spectra of synthetic clusters with ages of 10–25 Myr (RSG-dominated) and age differences of 2–3 Myr can be distinguished and sorted. TP-AGB stars leave potentially useful spectral signatures in integrated spectra of slightly older objects ([16]). Stochastic fluctuations in the integrated spectrophotometry, that are dominated by the most luminous red stars, add negligible amounts to the other dating errors as long as the clusters contain more than $10^4 M_{\odot}$ of stars [15].

Again, when enough telescope time can be obtained to combine several of the above approaches, ages can be expected to within a conservative $\pm 50\%$ (25% in favourable cases, 0.3 dex for sceptical attendees).

The ages discussed here are comparable to galaxy interaction timescales and more generally to the duration of starburst activity on galaxy scales. Mihos (this workshop) reminded us that the treatment of the transition from a dynamical perturbation to star formation in dynamical models is simplistic; delays of 100 to 500 Myr are found to be typical before onset of starburst activity. Obvious morphological signatures of an interaction fade away over similar timescales; in the case of NGC 4038/39 the spectrophotometric age distribution of the clusters is probably a safer indication of a second encounter than model adjustments to the projected system structure. In NGC 1614 and IC 342 (Rieke, Genzel, this session) starburst knots form a ~ 0.5 kpc nuclear ring, with younger knots (H α sources, ≤ 6 Myr old) located at larger galactic radii than older ones (RSG hosts, ≤ 7 Myr old). No dynamical models are as yet available to explain this situation well enough to require improved spectrophotometric ages.

Is the formation of generations of starburst clusters a recurrent phenomenon? When cluster ages become comparable to the dynamical timescales of a galaxy, age differences much shorter than this time cannot be interpreted as separate SF episodes, but rather as one extended one. Therefore a 50% precision on the age is sufficient to detect potential separate episodes. Then, attempts to compare properties of the starburst clusters of the current and the previous active phases must deal with a large variety of dynamical effects that rule the survival/destruction of starburst clusters over timescales of $10^8 - 10^9$ yrs [9]. Uncertainties in those are likely to wash out 50% age errors.

In this section again, our (biased) approach demonstrates that current age estimates pose challenging astrophysical problems that are far from being resolved to the point of necessitating better timelines.

4 Starburst galaxies at low spatial resolution

Let us finally question the dating of starburst galaxies observed at a spatial resolution no better than a few 100 pc, or completely unresolved. Partial spatial resolution has obvious advantages but also has some dangers: aperture mismatch between wavelengths, the likelihood that wavelength-dependent photon-exchanges with regions outside the line of sight (through scattering) falsify energy balances, the possibility that average obscuration curves don't apply, etc. The youngest and/or least reddened stellar component is usually dominant at UV wavelengths; but underlying "evolved" populations have been found in all starbursts. Age studies must also aim at determining whether these are part of an extended starburst episode that is still going on, or whether they are remnants of previous, dynamically unrelated star formation.

The nuclear starburst in the interacting spiral galaxy NGC 7714 will be used here for illustration. Integrated photometry is available over the whole electromagnetic spectrum. Extinction is very inhomogeneous and typically $A_v \sim 0.8$. A recent study [17] addresses the photometry and the UV+V+near-IR spectra of the central 300 pc. There, the UV is dominated by a young (~ 5 Myr old) burst, obviously seen through a hole in the dust distribution; the short wavelengths thus contain no information on putative other young populations, including those required to explain the far-IR emission. The broad band photometry can be adjusted satisfactorily with many models: continuous SF over as little as a few 10^7 yrs or as long as $\sim 10^9$ yrs, or a succession of brief bursts: dust distributions provide more than enough degrees of freedom. More stringent constraints come from spectroscopy: the Hubble Space Telescope UV spectrum favours the presence of at least one instantaneous 5 Myr burst; the Balmer line region rejects the optical predominance of populations younger than ~ 300 Myr or older than ~ 900 Myr (note that the continuum shape had to be used in addition to the line profiles of the rectified spectrum in order to reach this conclusion); the K band spectrum suggests mixed contributions, as opposed to a population purely dominated by RSG or by TP-AGB stars. The far-IR flux sets a loose upper limit on the amount of heavily obscured young stars, and the reddened Balmer ratio a lower one. The study concludes that starburst activity has been going on with ups and downs over an extended time, and that durations between ~ 300 and ~ 900 Myr are consistent with the data. This is an age to $\pm 50\%$.

The observational constraints on starburst studies can and must still be improved, using available instruments; but on the other hand, more dust configurations and the effects of chemical evolution must be explored systematically, adding even more free parameters. We will thus probably have to bear with $\pm 50\%$ estimates for a while.

Is that enough? In the case of NGC 7714, it is at least sufficient to point out an astrophysical problem: the comparison of the system morphology with dynamical simulations indicates that the closest encounter with NGC 7715 occurred about 100 Myr ago. The model parameters would allow to increase the time since interaction by about a factor of 2, but it seems difficult to reconcile

this dynamical timescale with the starburst timescales derived from spectrophotometry.

5 Conclusion

Although some workshop participants never accepted age uncertainty estimates below 0.3 dex, we believe that detailed multiwavelength studies, as possible with current instruments (when access to them is not a limiting factor), allow to reach $\pm 50\%$, or even better in particularly favourable configurations. The session has allowed many examples to be discussed, and we hope it has conveyed the positive impression that current age determinations, despite their uncertainties, are indeed providing essential constraints on theoretical issues related to starbursts.

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